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A comment on hadronic charm decays

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Abstract

We give arguments in favor of the compatibility with standard physics of some large nonleptonic branching fractions in Cabibbo–forbidden D^+ decays, contrary to a recent claim in the literature.

More than twenty years ago, the large difference between the lifetimes of charged and neutral D mesons has been attributed to the effect of the interference between color-favored and color-suppressed amplitudes in D^+ decays [1] and/or of the W-exchange contribution in the D^0 decay amplitudes [2]. Since the second explanation would imply (in its simplest form) a large annihilation contribution in D_s^+ and large branching ratios (BR's) for unobserved decay channels, the interference is commonly believed to be the main effect [3]. Concerning exclusive decays, the surprisingly large BR for the decay $D^0 \to \overline{K}^0\ \pi^0$ showed that the colour suppression is much less effective than expected [4, 5] in these decays. This fact may further point to important cancellations due to interference between color-allowed and color-(not-so-much)suppressed amplitudes in D^+ decays.

All the above applies to the (dominant) Cabibbo–allowed decays. In the Cabibbo–forbidden D^+ decays to two strange mesons, only the color-favored tree amplitude contributes (as it is also the case for D^0 decays in two charged particles). Therefore, the branching fractions for these decays might be considerably larger than what would be obtained with the simple–minded suppression by a factor $\tan^2\theta_C$ with respect to Cabibbo–allowed decay rates. The same is true for the doubly–forbidden decays $D^+ \to K^{(*)+}\ X$. The precise values of these BR's will however be affected by other effects, such as annihilation contributions and final state interactions (rescattering), and are therefore very model-dependent.

In a recent letter, Close and Lipkin [6] suggested that the measured BR's of the decays $D^+ \to K^{*+}\overline{K}^0$ (3.1 ± 1.4 %) [8] and $D^+ \to K^{*+}\overline{K}^{*0}$ (2.6 ± 1.1 %) [9], although affected

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by large error bars, would not be reproducible in the framework of the standard model[3]. We disagree on this conclusion. In fact, the key point of their argument consists in a nice relation between the rate for the $D^+ \to K^{*+}\overline{K}^0$ decay and the rate for D^0 decays into the state $K^*\overline{K}$, $I = 1$ (valid under the simplified assumption of dominance of the $\Delta I = 1/2$ amplitude). However, when in their eq.(17) they consider the branching fractions, they multiply by the ratio of D^+ and D^0 lifetimes the wrong side; as a consequence, their numerical result (a quantity $x < 0.6$ should be greater than another quantity which is instead $y = 4 \pm 2$) is modified to x (< 0.6) should be greater than $y' = 0.63 \pm 0.29$, which is of course easily acceptable, within error bars. The same comment applies to their considerations regarding the decay into two vector mesons, that we will not discuss any more in this paper.

Models that are able to describe the main features of the two-body D decay data without introducing any "new physics" have appeared in the literature [10, 11, 12, 13] since a long time. They are generally based on a modified factorization approximation, in which the color suppression factor and annihilation and W-exchange contributions are determined by fitting some parameters to the experimental data. In the following, to give an example of a model where the BR for $D^+ \to K^{*+}\ \bar{K}^0$ turns out to be large (1.52%), we present results from [14]. These were obtained making a fit with 15 parameters to all BR data for D decay in two pseudoscalar mesons (PP), a pseudoscalar and a vector meson (PV) and a pseudoscalar and a light scalar meson (PS) (corresponding to 56 experimental data points or upper bounds). Here, we will only discuss the fitted theoretical results for some particular decays, in order to illustrate the previous arguments. In particular, we will give results for decays to $\overline{K}^0$ and K^0 mesons separately, although in the fit decays in K_S were considered, since the neutral kaons are experimentally detected through their decays in two pions.

The annihilation/W-exchange contribution in the factorized approximation (*i.e.* neglecting possible gluon emissions from the initial quarks) depends on the matrix element of the divergence of a vector (axial-vector) current for PP (PV) decays. This is transformed, using the equations of motion, to the matrix element of a scalar (pseudoscalar) density multiplied by the difference (sum) of quark masses. As a consequence, the annihilation contributions to Cabibbo–allowed D_s^+ and to Cabibbo–forbidden D^+ decays are quite small, being suppressed by light quark masses. Relevant annihilation contributions are present instead for Cabibbo–forbidden D_s^+ and doubly–Cabibbo–forbidden D^+ decays.

The pattern arising for the factorized amplitudes may be strongly mixed up by final state interactions. In this model, all the states belonging to the same representation of the flavor SU(3) symmetry mix among themselves. The rescattering is dominated by the nearby resonances, whose experimental masses and widths (when known) determine the phase-shifts [4].

The results of the fit for some D^+ decay channels of interest are presented in Table 1. In the first column we list the branching ratios that would result prior to rescattering

[3]This conclusion has also been uncritically accepted in [7].

[4]A similar treatment of final state interactions has been recently presented in [15]. However, in that paper the phase shifts have been erroneously multiplied by a factor of two.

corrections (BR_{NR}) – not a fit to the data. The second column contains the final, rescattered results (BR_{RR}). In the third column we write the present experimental data [16] that in some cases differ slightly from the data that were fitted.

Table 1: Branching ratios (in %) for some nonleptonic decays of D^+ mesons.

$D^+ \to$	$\mathrm{BR_{NR}}$	$\mathrm{BR_{RR}}$	$\mathrm{BR_{exp}}$	$D^+ \to$	$\mathrm{BR_{NR}}$	$\mathrm{BR_{RR}}$	$\mathrm{BR_{exp}}$
$\pi^+\overline{K}^0$	2.939	2.939	—	$\rho^+\overline{K}^0$	14.076	12.198	—
				$\pi^+\overline{K}^{*0}$	0.076	1.996	1.92±0.19
$\pi^+\pi^0$	0.185	0.185	0.25±0.07	$\rho^+\pi^0$	0.775	0.451	—
				$\pi^+\rho^0$	0.012	0.104	0.104±0.018
$K^+\overline{K}^0$	1.486	0.764	0.58±0.06	$K^{*+}\overline{K}^0$	1.364	1.515	3.1±1.4
				$K^+\overline{K}^{*0}$	0.653	0.436	0.42±0.05
				$\phi\,\pi^+$	0.505	0.619	0.61±0.06
$K^+\pi^0$	0.083	0.055	—	$K^{*+}\pi^0$	0.096	0.057	—
				$K^+\rho^0$	0.012	0.029	0.025±0.012
$K^0\pi^+$	0.057	0.053	—	$K^{*0}\pi^+$	0.062	0.027	0.036±0.016
				$K^0\rho^+$	0.001	0.042	—
π^+K_S	1.088	1.347	1.38±0.09	ρ^+K_S	6.946	5.820	3.30±1.25

The left part of Table 1 refers to PP decays. We note that the two Cabibbo–forbidden decays have very different $\mathrm{BR_{NR}}$'s: this is due to the interference between "tree" and "color–suppressed" amplitudes, present in the $\pi^+\pi^0$ case (as well as in the Cabibbo–allowed decay to $\pi^+\overline{K}^0$) and absent for the $K^+\overline{K}^0$ decay, which has therefore a much larger BR. A similar argument also applies to the doubly–forbidden decays, that do not have interference and have instead possibly large annihilation contributions: their BR's are of the order of $\tan^2\theta_C$ $\mathrm{BR_{NR}}(D^+ \to K^+\overline{K}^0)$ and much larger than $\tan^4\theta_C$ $\mathrm{BR_{NR}}(D^+ \to \pi^+\overline{K}^0)$. The rescattering effects are quite big, and approximately half of the biggest Cabibbo–forbidden BR is redistributed to the other channels, namely $\pi\eta$ and $\pi\eta'$.

In the right part of Table 1, it can be noted that the naturally paired channels ($\mathrm{V}_i\mathrm{P}_j$ and $\mathrm{P}_i\mathrm{V}_j$) have very different BR's. The simplest case to analize is the $K^{*+}\overline{K}^0$ and $K^+\overline{K}^{*0}$ pair, that has no interference and very small annihilation contribution. In the factorized approximation, the first decay is induced by the VV part of the effective hamiltonian, the second by the AA part. The parameters entering in the calculation favor the first contribution, the main reason being the ratio of decay constants f_{K^*} / $f_K \simeq 1.4$. When also interference enters the game, the smaller BR's may be almost completely cancelled, as it happens for the Cabibbo–allowed case: it is very difficult to make a guess of the rates of Cabibbo–forbidden decays if one has such a spread in the Cabibbo–allowed BR's! The rescattering effects are not very big for the channels having large $\mathrm{BR_{NR}}$, while they obviously change a lot the smallest ones. The general pattern is however rather stable.

The results of the fit for some D_s^+ decay channels of interest are presented in Table 2.

Again, our comments refer to the results prior to rescattering corrections, listed in the first and fourth columns. It is to be noted that the branching ratios in final states containing a hypothetical $s\bar{s}$ pseudoscalar meson with the η mass would be approximately twice the values reported in the first line in Table 2, with the value for the $\eta-\eta'$ mixing angle that we use [17].

Table 2: Branching ratios (in %) for some nonleptonic decays of D_s^+ mesons.

$D_s^+ \to$	$\mathrm{BR_{NR}}$	$\mathrm{BR_{RR}}$	$\mathrm{BR_{exp}}$	$D_s^+ \to$	$\mathrm{BR_{NR}}$	$\mathrm{BR_{RR}}$	$\mathrm{BR_{exp}}$
$\pi^+\eta$	5.026	1.131	1.7±0.5	$\rho^+\eta$	9.182	8.122	10.3±3.2
				$\pi^+\phi$	5.065	4.552	3.6±0.9
$\overline{K}^0 K^+$	3.285	4.623	—	$\overline{K}^{*0} K^+$	4.108	4.812	3.3±0.9
				$\overline{K}^0 K^{*+}$	1.770	2.467	—
$\pi^+ K^0$	1.099	0.373	< 0.8	$\rho^+ K^0$	0.847	1.288	—
				$\pi^+ K^{*0}$	0.898	0.445	0.65±0.28
$\pi^0 K^+$	0.211	0.146	—	$\rho^0 K^+$	0.018	0.198	< 0.29
				ωK^+	0.288	0.178	—
				$\pi^0 K^{*+}$	0.177	0.076	—
$K^+\eta$	0.003	0.300	—	$K^{*+}\eta$	0.288	0.146	—
				$K^+\phi$	0.014	0.008	< 0.05
$K^+ K^0$	0.012	0.012	—	$K^{*+} K^0$	0.021	0.018	—
				$K^+ K^{*0}$	0.003	0.006	—
$K_S K^+$	1.450	2.473	1.80±0.55	$K_S K^{*+}$	0.704	1.096	2.15±0.70

We comment at first on the PP decays. A comparison of the color–favored decays (into $\pi^+\eta$, π^+K^0 and K^+K^0) shows that the ratios of Cabibbo–forbidden and doubly–Cabibbo–forbidden to the Cabibbo–allowed BR are, respectively, about 0.1 and 0.001, instead of the expected values ($\tan^2\theta_C \simeq 0.05$ and $\tan^4\theta_C \simeq 0.003$): this may be explained as the effect of a rather large annihilation contribution in the Cabibbo–forbidden decay, $D_s^+ \to \pi^+K^0$, and of an important interference in the doubly–Cabibbo–forbidden channel. Similar arguments hold for the color–suppressed decays. A discussion of the final state $K^+\eta$ would be more involved, since also the non-strange components of the η meson participate in this decay.

In the decays to PV final states, as it was noted for the D^+, those induced by the VV part of the effective Hamiltonian are larger than the others in the Cabibbo–allowed and doubly–forbidden cases. The Cabibbo–forbidden and color–favored decays $D_s^+ \to \rho^+K^0$ and $D_s^+ \to \pi^+K^{*0}$ are roughly equally frequent, as a consequence of large annihilation contributions, equal and opposite [5] in these two channels. The annihilation terms are also responsible of the big difference among the Cabibbo–forbidden and color–suppressed decays $D_s^+ \to \rho^0K^+$, ωK^+ and π^0K^{*+}. The rescattering corrections are often quite large,

[5] The opposite sign arises from the F–type coupling of the pseudoscalar density.

and the pattern discussed above is somehow hidden in the final results. However, it must be said that the general quality of the fit for D_s^+ decays is not very good, for example the prediction for $D_s^+ \to \rho^+\eta'$ is $\mathrm{BR}_{\mathrm{NR(RR)}} = 2.52(2.46)\%$ against an experimental value 12 ± 4 %. It may well be that some surprise will come out from new D_s^+ data, once better statistical and systematical accuracy is attained.

Table 3: Branching ratios (in %) for some nonleptonic decays of D^0 mesons.

$D^0 \to$	$\mathrm{BR}_{\mathrm{NR}}$	$\mathrm{BR}_{\mathrm{RR}}$	$\mathrm{BR}_{\mathrm{exp}}$	$D^0 \to$	$\mathrm{BR}_{\mathrm{NR}}$	$\mathrm{BR}_{\mathrm{RR}}$	$\mathrm{BR}_{\mathrm{exp}}$
π^+K^-	5.114	3.847	3.80±0.09	ρ^+K^-	17.029	11.201	10.2±0.8
				π^+K^{*-}	2.568	4.656	6.0±0.5
$\overline{K}^0\pi^0$	0.711	1.310	—	$\overline{K}^{*0}\pi^0$	1.024	3.208	2.8±0.4
				$\overline{K}^0\rho^0$	1.607	0.759	—
				$\overline{K}^0\omega$	0.345	1.855	—
K^+K^-	0.579	0.424	0.412±0.014	$K^{*+}K^-$	0.839	0.431	0.38±0.08
				K^+K^{*-}	0.101	0.290	0.20±0.11
				$\phi\ \pi^0$	0.098	0.105	< 0.14
$K^0\overline{K}^0$	0.0	0.130	0.071±0.019	$\overline{K}^{*0}K^0$	0.008	0.052	< 0.17
				$\overline{K}^0K^{*0}$	0.008	0.062	< 0.09
$\pi^+\pi^-$	0.500	0.151	0.143±0.007	$\rho^+\pi^-$	1.048	0.706	—
				$\pi^+\rho^-$	0.350	0.485	—
$\pi^0\pi^0$	0.052	0.115	0.084±0.022	$\rho^0\pi^0$	0.137	0.216	—
				$\omega\pi^0$	0.010	0.013	—
$K^+\pi^-$	0.048	0.033	0.015±0.02	$K^{*+}\pi^-$	0.059	0.039	—
				$K^+\rho^-$	0.015	0.025	—
$K^0\pi^0$	0.007	0.008	—	$K^{*0}\pi^0$	0.008	0.004	—
				$K^0\rho^0$	0.001	0.008	—
				$K^0\omega$	0.004	0.002	—
$K_S\pi^0$	0.428	0.759	1.14±0.11	$K_S\rho^0$	0.842	0.446	0.735±0.145
				$K_S\omega$	0.212	0.973	1.1±0.2

In Table 3 we have reported for completeness the data and predictions for some exclusive D^0 decays. Comments analogous to those given on the other Tables could be made: we only note that rescattering effects are essential to allow the decays into a pair of strange neutral mesons.

It may be of some interest to consider partially inclusive rates of Cabibbo–allowed (CA), forbidden (CF) and doubly–forbidden (DCF) decay processes. For such quantities the comparison of experimental data with theoretical predictions are much less dependent on the rescattering corrections. Their ratios may then be compared with the appropriate power of $\tan\theta_C$ to check if the simple–minded suppression (CF/CA $\simeq 2\ \tan^2\theta_C$ and DCF/CF $\simeq 0.5\ \tan^2\theta_C$) gives an adequate description of the data. This is illustrated in

Table 4: Inclusive branching ratios (in %) for two-body decays of D mesons.

		CA	CF	DCF	CF/CA	DCF/CF
$D^0 \to$ PP	exp.	8.71±0.38	> 0.68		> 0.075	
	th.	7.34	1.31	0.057	0.18	0.043
$D^0 \to$ PV	exp.	25.4±1.2	> 0.44		> 0.02	
	th.	23.0	2.68	0.085	0.12	0.032
$D^+ \to$ PP	exp.	2.77±0.18	> 1.43		> 0.44	
	exp.		< 2.56		< 0.92	
	th.	2.94	2.10	0.164	0.71	0.078
$D^+ \to$ PV	exp.	8.5±2.5	> 2.6		> 0.24	
	th.	14.2	3.35	0.205	0.24	0.061
$D_s^+ \to$ PP	exp.	9.2±1.6				
	th.	11.2	1.31	0.012	0.12	0.009
$D_s^+ \to$ PV	exp.	32.4±4.6				
	th.	25.1	2.37	0.024	0.094	0.010

Table 4, that we now comment upon.

The success of the theoretical model in describing the data is generally acceptable. The worst case is given by the Cabibbo–allowed $D^+ \to$ PV decays, where the theoretical predictions are considerably larger than experiment.

Concerning the inclusive data and theoretical predictions for D^0 decays, the simple–minded suppression referred to above is a consequence of (flavor) SU(3) symmetry. In the limit of total decoupling of the third quark family, the weak effective hamiltonians form a U-spin triplet, the D^0 meson has zero U-spin and therefore one has only one decay amplitude [18, 19, 12, 20, 21]. Moreover, the annihilation contributions to decays into PP vanish for CF, are SU(3) violating and of opposite sign for CA and DCF, while they are nonvanishing and SU(3) allowed for decays to PV. These features give a reasonable explanation of the results for the ratios, both bigger than naively expected in PP decays and near to the naive expectations in PV decays.

The charged and charmed mesons form a U-spin doublet. As a consequence, even in the symmetric limit, we have two independent decay amplitudes, and one would recover the simple-minded suppression factors only if these two amplitudes were equally important. More generally, SU(3) symmetry would predict the following relations

$$\left(\frac{\mathrm{CF}}{\mathrm{CA}}\right)_{D^+} \cdot \left(\frac{\mathrm{DCF}}{\mathrm{CF}}\right)_{D_s^+} = \left(\frac{\mathrm{CF}}{\mathrm{CA}}\right)_{D_s^+} \cdot \left(\frac{\mathrm{DCF}}{\mathrm{CF}}\right)_{D^+} = \tan^4\theta_C \ , \tag{1}$$

both for PP and for PV final states. From Table 4 one obtains for the three terms in the above equation the numerical results (0.0064, 0.0094, $\tan^4\theta_C = 0.0026$) for PP decays and

(0.0024, 0.0057, 0.0026) for PV decays. This shows that the flavour symmetry is rather badly broken in this factorized model, without any need of "new physics".

The inclusive data of D^+ show once more that the ratio CF/CA is much larger than the (very) naive expectation, due to destructive interference in the Cabibbo–allowed amplitudes. This is particularly evident for the decays into PP, although no single branching fraction is larger than 1%. The ratio DCF/CF is also larger than expected, due to the annihilation contribution in DCF.

The predictions for D_s^+ inclusive decays (the data are still too sparse to give indications) suggest that, while CF/CA is "normal", the ratio DCF/CF is smaller than naively expected, due to interference effects in DCF.

Decays in two vector mesons are not included among those fitted in our model, so that we are not able to present a theoretical estimate of the other large BR($D^+ \to K^{*+}\overline{K}^{*0}$).

In this paper, we have shown that in a model for D decays based on (generalized) factorization and including resonance–mediated final state interactions it is possible to get a branching ratio for the Cabibbo–forbidden channel $D^+ \to K^{*+}\overline{K}^0$ of about 1.5%. In fact, an even larger prediction for this BR was given in a previous version of the model [12] prior to the experimental result. Therefore, we believe that it is not necessary to invoke "new physics" to explain the experimental datum on this decay.

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